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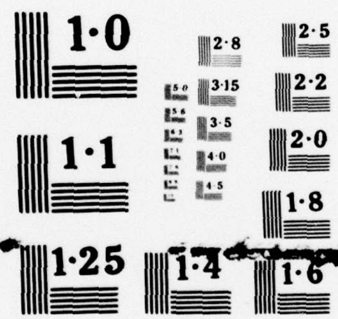

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(6) **Vorticity Measurements Using Calibrated Vane-Vorticity Indicators and Comparison with X-Wire Data**

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VORTICITY MEASUREMENTS USING
CALIBRATED VANE-VORTICITY INDICATORS AND
COMPARISON WITH X-WIRE DATA+

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Abstract

Vane-type vorticity indicators of various sizes have been constructed, calibrated and used for direct and rapid measurement of local mean streamwise vorticity in several swirling flows. The dependence of their calibration factor, which relates the vane rotational speed to the local angular velocity of the fluid, on the free-stream velocity, the fluid rotational speed, and the transverse vorticity gradient was determined. When the vanes were carefully calibrated, and regularly checked and maintained, good agreement was achieved between vorticity profiles obtained using them and X-wire data. Otherwise, a vane can only be used to give an indication of vorticity.

Nomenclature

Symbol	Description
N_f	Angular velocity of the fluid in revolutions per minute
N_v	Angular velocity of the vane-vorticity indicator in revolutions per minute
r	Radial distance measured from the center of the test section
U_∞	Free-stream mean velocity
W	Vertical velocity in the fluid normal to the streamwise direction
x	Axial or streamwise distance
y	Lateral distance normal to streamwise direction and measured from the center of the test section
z	Vertical distance normal to streamwise direction and measured from the center of the test section
α	Half-angle setting between the airfoils
η	Vane indicator ratio
τ	Delay time in autocorrelation function
Ω_x	Vorticity in the streamwise direction

I. Introduction

Measurements of the streamwise vorticity component, i.e., the component of vorticity in the flow direction, can be made by one of several methods. Many of these methods rely on inferring the vorticity from measurements of the transverse velocity components and their spatial variations. One method which attempts to directly measure this vorticity component utilizes a mechanical device which we call the vane-vorticity indicator. Similar devices have been used by other experimenters for purposes of demonstration and for measurements. However, it is usually not clear what calibration factors were involved in the determination of the magnitude of the vorticity and how these factors were established. Along with simple construction and measuring techniques, determination of such factors and their dependence on other parameters, such as free stream velocity, would provide a useful tool for the direct measurement of such an important, but most difficult to measure, quantity.

Recently, Zalay[1] presented a comparison between measurements of the circulation around wing trailing vortices based on the evaluation of vorticity by several methods including the vane indicator. His comparison demonstrates that for some trailing vortices "the vorticity meter significantly underestimated the strength of the vortex field," e.g., as much as 65% difference. Zalay concludes that vane-vorticity meters "behave in a nonlinear fashion in weak vortex fields" and notes that "no study has been done to compare the 'vane' vorticity meter with other flow measuring devices." He also suggests that this information may help in explaining the low vortex circulations cited in references such as that of McCormick et al.[2] In most of the previous studies, including those of Zalay and McCormick et al., the vorticity meter was calibrated by attaching a "calibration collar," a fixed-vane-type swirl generator, upstream of the device. Such procedure can only reveal the dependence of the calibration on the free-stream velocity, as evidenced by the results of these studies. In general, the calibration of a particular vane will depend as well on the fluid rotation velocity and the radial gradient of the angular velocity of the fluid.

In the present study, a systematic calibration of several vane-vorticity indicators is carried out and the dependence of the calibration factors on the various parameters is investigated. Next, the probes are used to measure the streamwise vorticity in several vortical flows and the results are compared with data obtained by x-wire anemometers. Finally, examples of the application of the vane indicator for direct and rapid evaluation of streamwise vorticity are summarized.

II. Probe Construction and Instrumentation

The vane vorticity indicator consists of four perpendicular blades, and is designed to rotate about its axis on a high-speed steel shaft, as shown in the photograph and by the schematic of Figure 1. The vanes are milled from either brass or aluminum stock, with the dimensions as given. The blades of the vane are made very thin in order to minimize the moment of inertia and to make the vane as sensitive as possible to variations in the flow. Initially, no teflon bushings or washers were used, but during the calibration procedures, excessive friction and wear made this modification necessary. The teflon inserts are replaceable, making the lifetime of the vane unlimited. More recent modifications include vanes with even thinner blades and the use

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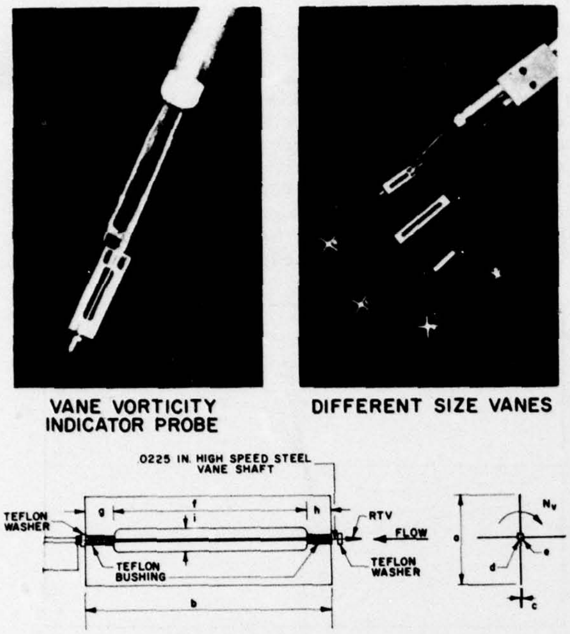

VANE NO.	MADE BY	a IN.	b IN.	c IN.	d IN.	e IN.	f IN.	g IN.	h IN.	i IN.
1	F. ROBERTS	.25	.562	.012	.027	.0225	.37	.116	.077	.078
2	G. GINANI	.375	.5	.017	.026	.0225	.37	.065	.065	.062
3	R. WIGELAND	.25	.438	.015	.028	.0225	.3	.093	.045	.046
4	J. FOSS	.375	.75	.014	.027	–	.5	.114	.136	.062
5	F. ROBERTS	.375	.625	.015	.027	–	.37	.15	.11	.062

Figure 1. Schematic of Vorticity Indicator Vanes and Dimensions, and Photographs of Different Size Vanes and Vane Vorticity Indicator Probe

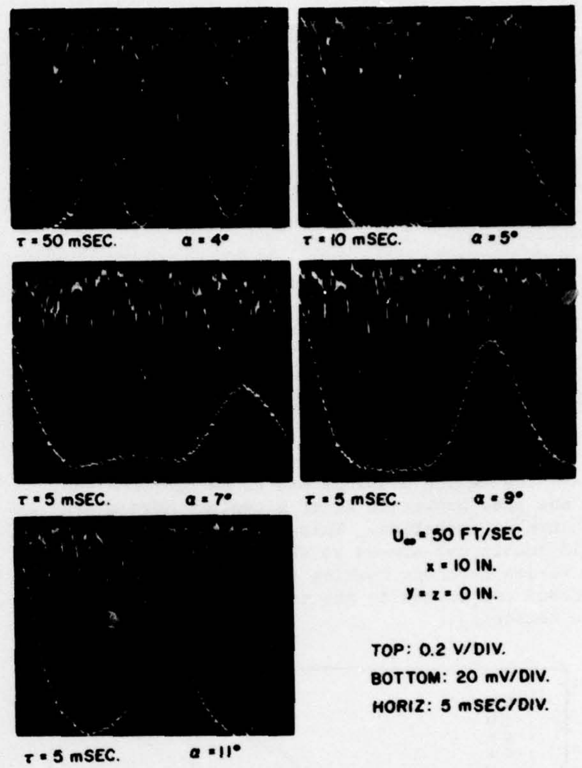

Figure 2. Sample Oscillograms of Signal From Vane Vorticity Indicator (Top Trace) and Its Autocorrelation Function (Bottom Trace) for Different Angles of Airfoils

of jewel bearings for even longer bearing life and lower friction.

When a vane is placed in the flow so that the vane rotation axis is aligned with some mean flow direction, the vane will spin only when there is a rotating component of the flow in this direction. The rotation of the vane can be related to the corresponding vorticity component through careful calibration. One of the most important considerations is a means of measuring the rotation of the vane without imparting any load to the vane, so as not to inhibit the rotation. The method used here employs a hot-wire located directly downstream of the vane and is similar to the method of Holdeman and Foss.[3] A photograph of the vane indicator probe with the vane and hot-wire in position is also shown in Figure 1. As the vane rotates, the wake from each blade will be detected as it passes over the hot-wire. This is shown by the top oscilloscope trace in each photograph in Figure 2, where each one is taken in slightly different flow conditions. For all of the cases, the hot-wire signal has spikes caused by the passage of the wakes of the vane blades and which are clearly visible due to the relatively low level of background turbulence. Time-averaged autocorrelation of the hot-wire output provides a signal from which the average rotational speed of the vane can be calculated. The lower trace in each photograph in Figure 2 is the resulting autocorrelation function, where the time delay τ varies across the photograph from zero to the value listed in each case. The peak in the autocorrelation function occurs at the time delay corresponding to one-quarter revolution of the vane.

III. Vane Calibration

All of the traces in Figure 2 were recorded in the flow conditions used for calibration of the vanes, i.e., the trailing vortex generated by two adjacent airfoils hinged along the same axis at their quarter chord position and set at equal but opposite angles of attack. Varying the angle of attack for a fixed free stream velocity, as done in Figure 2, curves are obtained relating vane rotational speed N_v to angle of attack α. During calibration the vane rotational axis is positioned along the streamwise direction in the center of the trailing vortex with the vane located 10 inches downstream of the trailing edge of the airfoils. Careful probing of the airfoils' generated vortices at this position demonstrated their axial symmetry[4,5].

Two curves for one vane, Vane #1, at two free stream velocities, are plotted in the top part of Figure 3. For both velocities, the same trends are found as the angle of attack of the airfoils is changed. The vane rotational speed generally increases as the angle of attack is increased, but there are some regions where this is not the case, such as around 3 degrees. Since these regions occur for different values of α and N_v as the free stream velocity is changed, they are believed to be a result of changes in the flow over the

airfoils and not of any mechanical difficulties (for further details see Reference 4). In addition, the minimum angle of attack necessary for vane rotation, which is indicative of the threshold caused by friction in the bearings, decreases as the velocity increases. The higher free-stream velocities produce a stronger vortex for the same angle of attack, so the torque required to overcome the bearing friction occurs at a smaller angle of attack.

Results for three different size vanes are plotted in the lower part of Figure 3. The similarity of the results for all three, along with the above observations, led to the designation of the level of performance of Vanes #1 and #2 as the calibration conditions for any vane constructed using the teflon bushings. During the course of experiments, the vane is periodically checked against these curves to ensure the validity of the data. The teflon bushings had to be replaced and the new ones broken in after a typical period of 30 hours of operation. This period depends on the fluid rotational speeds in which the vane is used and varies from one bushing to another, so that frequent comparison to the calibration conditions is a necessity.

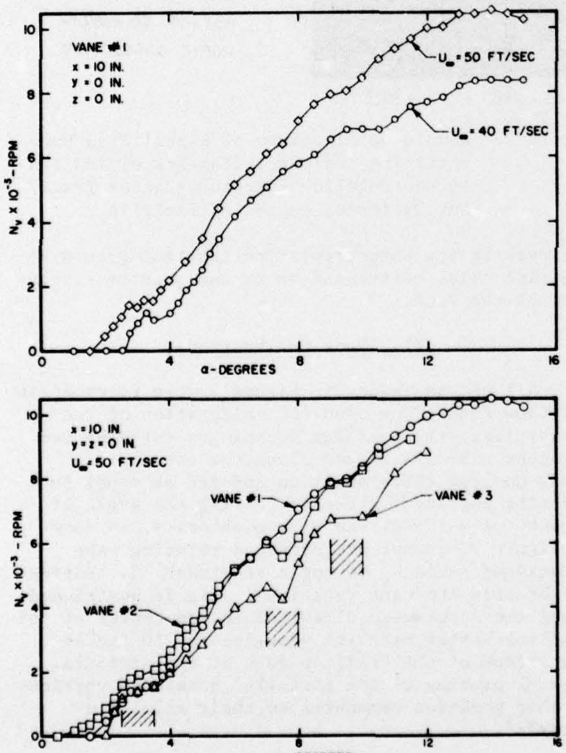

Figure 3. Calibration of Vorticity Indicator Rotational Speed for Vane #1 and Comparison for Vanes #1, #2 and #3 Versus Airfoil Angle

Since the rotational speed of the vane is known for various angles of attack and free stream velocities, data on the local velocity components in these flow conditions can provide the basis for determining how well the vane measures vorticity in the flow. The tangential velocity as a function of the radius from the center of the vortex was measured with an x-wire probe in this calibration flow condition at the same downstream location as the vane during calibration. Samples of these traverses are given in Figure 4 for several angles of attack. The solid body core of the vortex is approximately the same size for all of the cases shown. The slope of the velocity profile in this region is used to calculate the angular velocity of the core, called the solid body rotation speed.

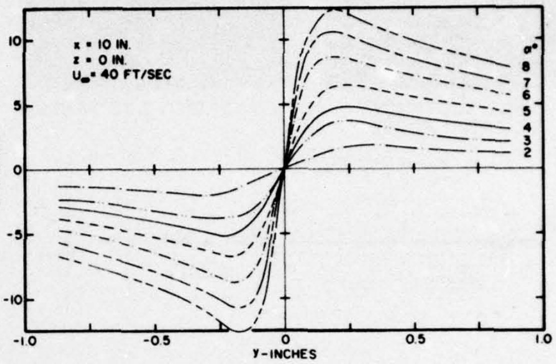

Figure 4. Lateral Profiles of Vertical Mean Velocity Through Vortex of Airfoil Swirl Generator for Various Angles of Attack

However, considering the dimensions of the vanes, e.g., Vane #1, we find that the vane extends slightly beyond the region of solid body rotation. Another rotational speed based on the velocity at the tip of the vane is defined, assuming an equivalent solid body rotation velocity profile across the vane, and is called the vane width speed. Comparison of the rotational speed of the vane with these fluid rotational speeds provides a calibration factor which is used to convert the vane data. Depending on the size of the vane, the true speed to be used in the calibration is probably somewhere between these two limits.

In general, this calibration factor may be a function of the fluid rotational speed, the free stream velocity, the radial vorticity gradient, or the physical dimensions of the vane. Forming a ratio of the vane rotational speed N_v to the fluid rotational speed N_f, the calibration factor is called the vane indicator ratio η, and has two values for each N_v depending on which N_f is used, i.e., *either the solid body rotation speed or the* vane width speed.

To demonstrate the effect of the fluid rotational speed on the value of η, the calibration curves can be used. Choosing $\eta = 0.5$, the comparison shown in the top part of Figure 5 is obtained. This constant value of η causes most of the vane data to follow the x-wire results except for low vane rotations. One may conclude that η is somewhat independent of the fluid rotational speed, at least for the higher vane speeds. This conclusion is supported by the lower part of Figure 5, where the detailed variation of η with vane rotational speed is plotted for the two fluid rotational speeds. The value of η is almost constant for speeds over 3000 rpm, and decreases nonlinearly for lower rotational speeds.

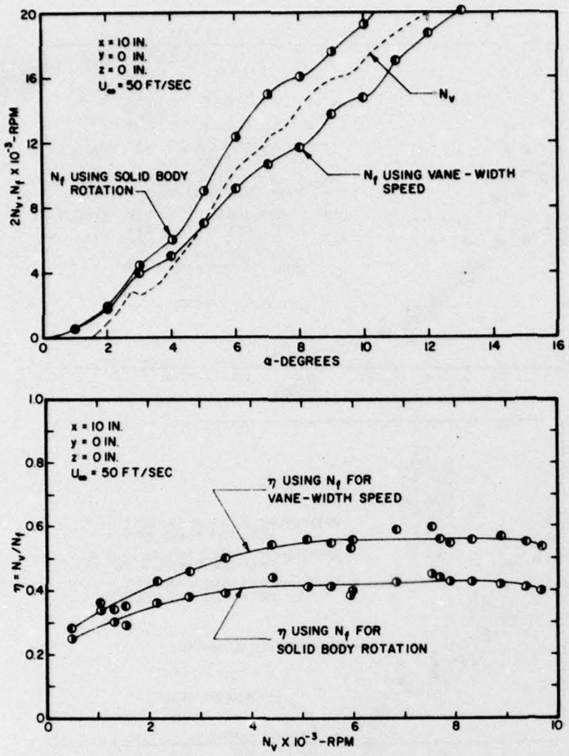

Figure 5. Fluid Rotational Speed and Vorticity Indicator Rotational Speed Using $\eta = 0.5$ as a Function of Airfoil Angles at 50 ft/sec., and Variation of η with Vorticity Indicator Rotational Speed for Vane #1

To determine the effect of the free stream velocity on the value of η, the free stream velocity is varied for a fixed angle of attack, as shown in Figure 6. Here the value of η is again 0.5, as indicated by the vertical axis scale. The converted vane data follow closely the calculations of N_f from the x-wire measurements based on the vane width speed. If a slightly different value of η is used, the vane results will follow the data for solid body rotation. In either case, the ratio η appears to be only a slight function of free stream velocity over this range.

Before examining the effect of the radial vorticity gradient, further discussion on the effect of vane size is needed. As mentioned earlier, calibration curves for three different vanes are presented in the lower part of Figure 3. Vane #2 is 50% wider and almost the same length as Vane #1, while Vane #3 is the same width as Vane #1, but is about 25% shorter. The agreement between Vane #1 and Vane #2 is quite good, as noted earlier, but Vane #3 rotates at slightly slower speeds, mainly due to construction differences with resulting additional friction. This figure shows that the ratio η is independent of the width and probably also independent of the length for the range of calibration conditions and vane sizes used. Details of the calibration curves, particularly over the hatched ranges of α, are also repeated for the different size vanes at the same angle of attack, i.e., fluid rotational speed in the vortex. This

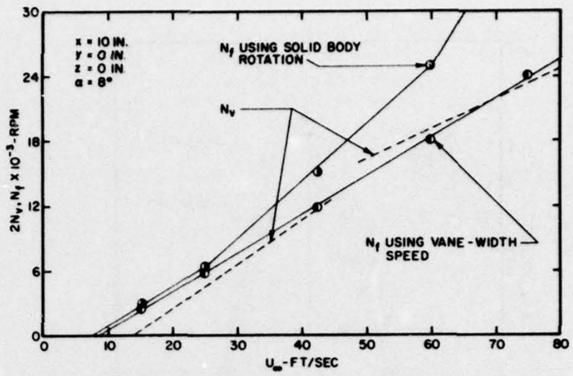

Figure 6. Fluid Rotation Speed and Twice the Vorticity-Indicator Rotational Speed as a Function of Free-Stream Velocity

also supports the earlier conclusion that these areas are caused by changes in the flow.

The effect of the vane width can be demonstrated more directly by using radial profiles of the vane rotational speed across the vortex as shown in Figure 7. In the top part of this figure, the profile for Vane #2 is similar to that for Vane #1, except at the base. The value for the half-width, $(b_{1/2})_z$, is the same for the two vanes. The extra width at the base is mainly due to the larger size of Vane #2, and to a lesser extent to the different thresholds of rotation observed for the two vanes in Figure 3.

A more graphic display of the effect of vane width and friction is shown in the bottom part of Figure 7. Obviously the difference in size between Vane #1 and Vane #2 cannot account for the discrepancy at larger distances from the center of the vortex. However, considering the rotational speed of Vane #2 in this area, and comparing with the aid of the calibration curves, we find that the rotation of Vane #2 corresponds to an angle of attack α for which Vane #1 does not rotate. Whether this is an effect of friction alone, size alone, or a combination of lower friction and increased size is not known, but it appears that the larger vane is more useful for measurements of low values of vorticity. Having noted the effects of angular velocity, free stream velocity, and physical size, only the effect of radial gradient of vorticity has yet to be demonstrated. This can be done as the vane data are being compared to the x-wire data in terms of vorticity.

IV. Vorticity Comparisons

The radial profiles of streamwise vorticity for each of the test flows are calculated using the x-wire data for the tangential velocity, as presented in Figure 4, assuming axial symmetry, and taking derivatives graphically. The radial profiles of vane rotation obtained from the vane vorticity indicator, such as those shown in Figure 7, are converted to the equivalent fluid rotational speeds using curves similar to those in the lower part of Figure 5. Then, since the vorticity is twice the angular velocity of the fluid, the vorticity measured by the vane is obtained. However, the calibration curves for the vanes were taken when the vane was in a region of almost constant

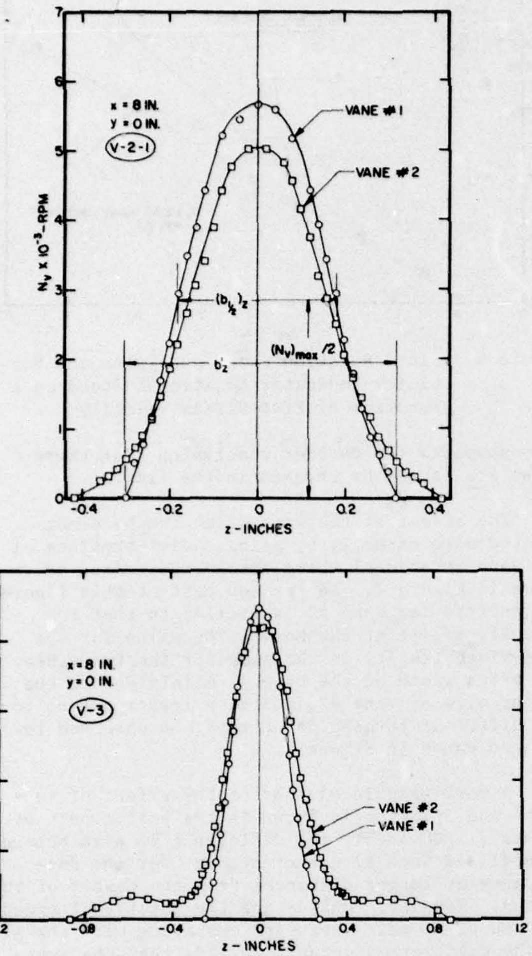

Figure 7. Radial Distribution of Vorticity Indicator Rotation in Test Flow Conditions "V-2-1" and "V-3" for Vanes #1 and #2

vorticity, i.e., in the solid body core of the vortex. The vane is in such a region only in the center of the vortex; at other radial positions, the vorticity is varying across the vane. If the gradient of vorticity has an effect on the value of η , the agreement would not be very good between the vorticity profile obtained using the converted vane data and that from the x-wire.

Some of these comparisons are shown in Figure 8, where both the lateral and vertical radial distributions are given. The converted vane data follow the vorticity calculations for the x-wire measurements very well in the region from the center of the vortex out to a position where the vorticity is too low for the vane to rotate because of frictional effects. In particular, conversion of the vane data using the values of η determined with the solid body rotation speed gives better results in the center of the vortex, while either fluid rotational speed can be used outside the core region. This good agreement demonstrates that the value of η is independent of the vorticity gradient, at least for Vane #1 and the range of the present calibration conditions, and that the vane does give a good measure of the vorticity in the flow.

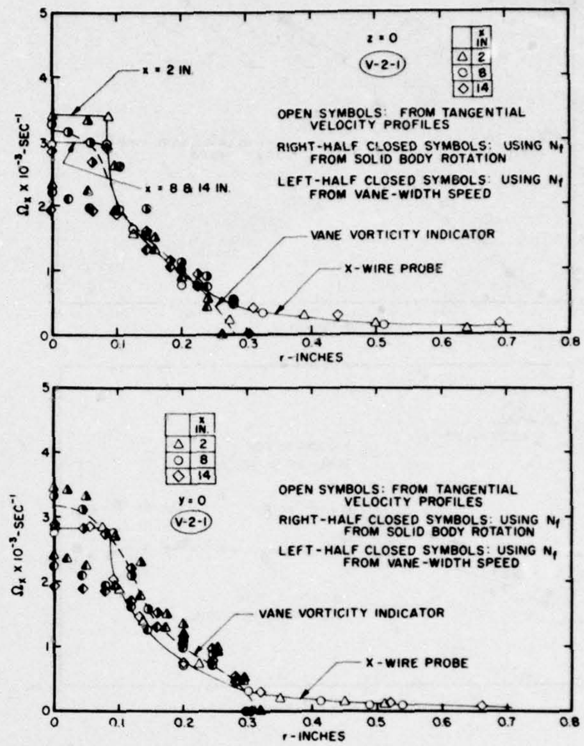

Figure 8. Comparison of Local Streamwise Vorticity as Obtained From X-Wire Data and From Vane Vorticity Indicator Measurements for Lateral and Vertical Distributions in Test Flow Condition "V-2-1"

While discussing the lower part of Figure 7, in the last section, it was noted that the larger vane might be more effective for measurements of low levels of vorticity. To demonstrate this, the profile of vane rotational speed was converted to vorticity, and is compared to x-wire results in Figure 9.

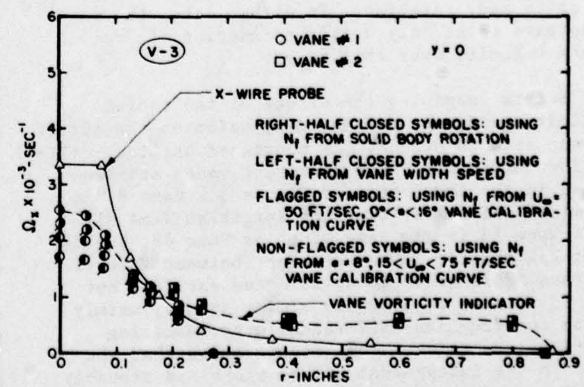

Figure 9. Comparison of Vertical Distribution of Local Streamwise Vorticity as Obtained from X-Wire and From Measurements of Vorticity-Indicator with Vanes #1 and #2 in Test Flow Condition "V-3"

While this vane does give information far away from the center, there are several errors in this comparison. The magnitude of the vorticity from the two methods does not agree anywhere. This error is caused by using extrapolated values for η since flow condition "V-3" is outside the range of the calibration conditions available for this vane. Even though the value of η is only a slight function of velocity, as shown in Figure 6, the errors can still be appreciable if the flow condition is far enough outside the range of calibration. This result is one of the most important conclusions to be realized when using the vane-vorticity indicator. The vane can only be used to measure vorticity when it is operating within the range of calibration. Outside of this range, it can only be used to give indications of vorticity.

In addition to the error in the magnitude of vorticity, there is also an error in the shape of the curve. As the x-wire results show, the vorticity decreases steadily with increasing radius. However, the vane data show a slight increase as the radius increases at some distance from the center. This is caused by errors in measuring very small values of vorticity, as has been noted by other experimenters[1] as well. It is not yet known whether this error is due to the large size of the vane, some nonlinearity and hysteresis effects near the threshold of rotation (see Figures 3 and 5) or some other effect.

V. Recent Improvements and Applications

As mentioned previously, in an effort to reduce the bearing friction in order to extend the useful range of the vanes, jewel bearings were mounted in some of the vanes. An example of the improvement in performance is given in Figure 10.

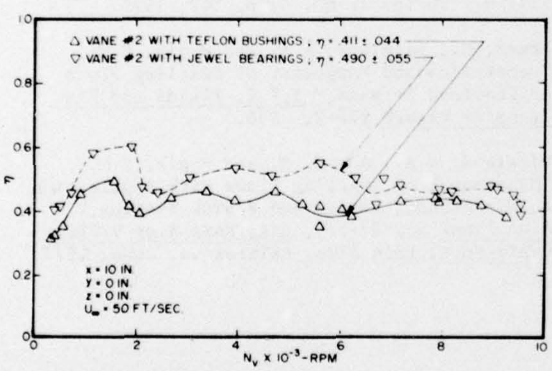

Figure 10. Comparison of the Vane Indicator Ratio for Teflon Bushings and Jewel Bearings for Vane #2

Here the vane indicator ratio η is plotted for Vane #2 both with teflon bushings and jewel bearings. The value of η is increased for every value of N_v, and the average value of η is increased from .411 to .490, which indicates a significant reduction in the bearing friction. At low vane speeds though, the nonlinear behavior of η with N_v is the same for either type of bearing, which means that this behavior is characteristic of Vane #2. This can also be demonstrated by contrasting the shape of the η vs. N_v data for Vane #2 in Figure 10 with the data for Vane #1 in Figure 5. In any case, the jewel bearings should extend the range for measurements in weak vortex flows, especially for the smaller vanes, but care must be taken to keep errors to a minimum through proper calibration.

So far, it has been demonstrated that the vanes provide a good method for direct and rapid measurement of the streamwise vorticity in the flow when the data are interpreted using appropriate calibration conditions. An example which shows the useful range of the signal processing scheme used here is presented in Figure 11. Not only do the autocorrelation functions show how uniform the indicated rotation of the vane is, as depicted by the many peaks when the range of τ is increased, but also that it is possible to obtain information even when the peaks from the blade wakes are not visible in the hot-wire output trace, as in the high-turbulence flow condition "SJ-1". (For the detailed description of flow condition "SJ-1" the reader is referred to Ahmed et al.[4,5])

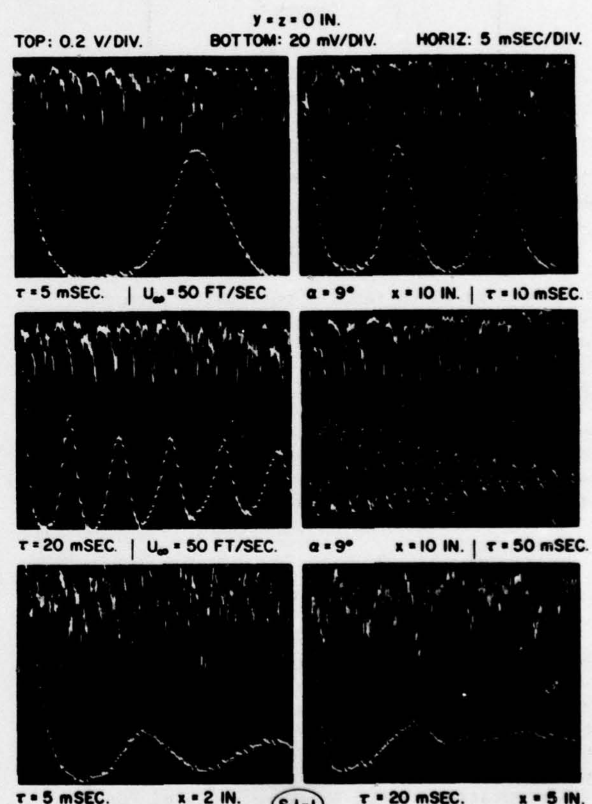

Figure 11. Sample Oscillograms of Signal From Vane Vorticity Indicator (Top Trace) and its Autocorrelation Function (Bottom Trace) Using Various Correlation Time Constants and Different Flow Conditions

This versatile means of measuring the streamwise vorticity was extensively used in experiments on the control of swirling and secondary flows in ducts and wind tunnels. The objective was to determine the effect of standard flow manipulators, such as screens and honeycombs, on different types of swirling flows. After documenting the flow using the vane vorticity indicator, traverses

downstream of the flow manipulators in directions parallel and normal to the face of the manipulator provide data from which the amount of swirl removed can be calculated. Samples of some traverses parallel to the manipulator are shown in Figure 12.

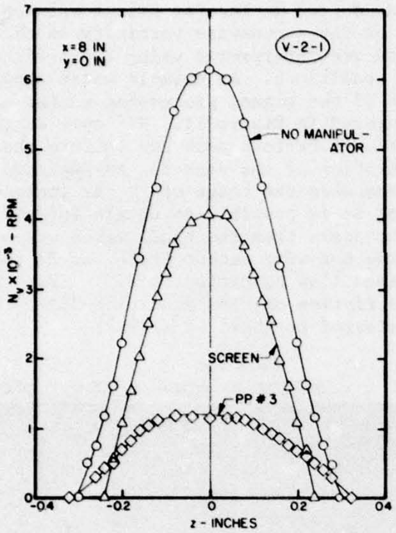

Figure 12. Effect of Screen and P.P. #3 on Vertical Distribution of Vorticity-Indicator Rotation in Test Flow Condition "V-2-1"

The perforated plate removes more swirl from the flow than the screen, although the screen does remove a substantial amount of swirl from the flow. Information such as this not only demonstrates the relative effectiveness of the manipulators, but can also provide insight into some of the mechanisms involved in removing the swirl. Further information on this subject can be found in Ahmed et al.[4,5] In these studies extensive measurements were made possible due to the rapid evaluation of the streamwise vorticity by calibrated vane vorticity indicators.

VI. CONCLUSIONS

Miniature vane vorticity indicators are very useful tools for the direct and rapid evaluation of streamwise vorticity. Utilizing advanced signal processing techniques, the vanes can be used in turbulent flows, even those with high turbulence intensities. For carefully constructed and balanced vanes, the calibration factor η relating the vane rotation to the local rotation of the fluid is only a slight function of the angular velocity of the fluid (except at low vane rotations), the free stream velocity, the physical dimensions of the vane, and the radial gradient of vorticity, for the range of vane sizes and calibration conditions used here. However, we find that the value of η does not increase monotonically with free stream velocity, as others have reported[1,2], but appears to reach a maximum around the middle of the velocity range we considered. Also, our values of η are somewhat lower than those found in these references, and have a nonlinear dependence on low fluid rotational speeds.

These vane characteristics emphasize the need for extensive calibration as presented in this paper. The vanes must be calibrated in flows which have known rotational characteristics as determined by some other accurate means of measurement, e.g., x-probe hot-wire anemometers. The performance of the vanes must also be frequently checked with these calibration conditions to ensure validity of the data. Further information on the calibration of the vanes and the methods used can be found in the report by Ahmed et al.[4]

In summary, when using proper calibration curves, the vanes accurately measure the streamwise vorticity in the flow. Without these calibration curves, or outside their applicable ranges, the vane can only be used to provide an indication of the vorticity, and the circulation inferred from the measurements may contain substantial errors.[1]

VII. Acknowledgments

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VIII. References

1. Zalay, A.D., "Hot-Wire and Vorticity Meter Wake Vortex Surveys," AIAA Journal, Vol. 14, No. 5, p. 694, 1976.

2. McCormick, B.W., Tangler, J.L. and Sherrieb, H.E., "Structure of Trailing Vortices," Journal of Aircraft, Vol. 5, No. 3, p. 260, 1968.

3. Holdeman, J.D. and Foss, J.F., "The Initiation, Development and Decay of the Secondary Flow in a Bounded Jet," Journal of Fluids Engineering, Vol. 97, Series 1, No. 3, p. 342, 1975.

4. Ahmed, M., Wigeland, R.A. and Nagib, H.M., "Generation and Mangement of Swirling Flows in Confined Streams," I.I.T. Fluids and Heat Transfer Report R76-2, 1976.

5. Wigeland, R.A., Ahmed, M. and Nagib, H.M., "Management of Swirling Flows with Application to Wind-Tunnel Design and V/STOL Testing," AIAA Paper No. 77-585, AIAA/NASA Ames V/STOL Conference, Palo Alto, California, June, 1977.

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15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

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18. SUPPLEMENTARY NOTES

The findings in this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Vortices
Guide vanes
Measurement
Velocity

20. ABSTRACT (Continue on reverse side if necessary

Vane-type vorticity indicators of various sizes have been constructed, calibrated and used for direct and rapid measurement of local mean streamwise vorticity in several swirling flows. The dependence of their calibration factor, which relates the vane rotational speed to the local angular velocity of the fluid, on the free-stream velocity, the fluid rotational speed, and the transverse vorticity gradient was determined. When the vanes were carefully calibrated, and regularly checked and maintained, good agreement was achieved between vorticity profiles obtained using them and X-wire data. Otherwise, a vane can only be used to give an indication of vorticity.

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